Beam Screen Design Concepts

O. Gröbner
CERN, LHC

The beam duct of the VLHC will be subjected to various sources of beam related power losses which, for cryogenic and vacuum reasons, need to be intercepted by an actively cooled beam screen. Starting from the ongoing design work for the LHC the dominating effects like synchrotron radiation, beam induced electron multipacting and image currents are discussed. The optimised design of a beam screen must satisfy in addition stringent vacuum requirements.

Credits :
V. Baglin, I.R. Collins, P. Cruikshank, B. Henrist, N. Hilleret, B. Jenninger, N. Kos, J.-M. Laurent, M. Jimenez, O.B. Malyshev, M. Pivi, F. Ruggiero, P. Strubin, F. Zimmermann

Beam Induced Heat Loads (1)

Nuclear Scattering

$$P(W/m) = \frac{1}{c}\frac{I\,E}{\tau} = 0.93\,\frac{I(A)\,E(TeV)}{\tau(h)}$$

LHC design requires a nuclear scattering lifetime of ~ 100h
LHC -> 0.1 W/m for two beams at ultimate current
Required gas density equivalent to 10^{15} H_2/m^3
VLHC: the lower nominal beam current will compensate the higher beam energy

Beam Induced Heat Loads (2)

Synchrotron Radiation Power

$$P(W/m) = 1.24 \cdot 10^3 \frac{E^4(TeV)\, I(A)}{\rho^2(m)}$$

Linear Photon flux

(photon stimulated molecular desorption and photoelectron production)

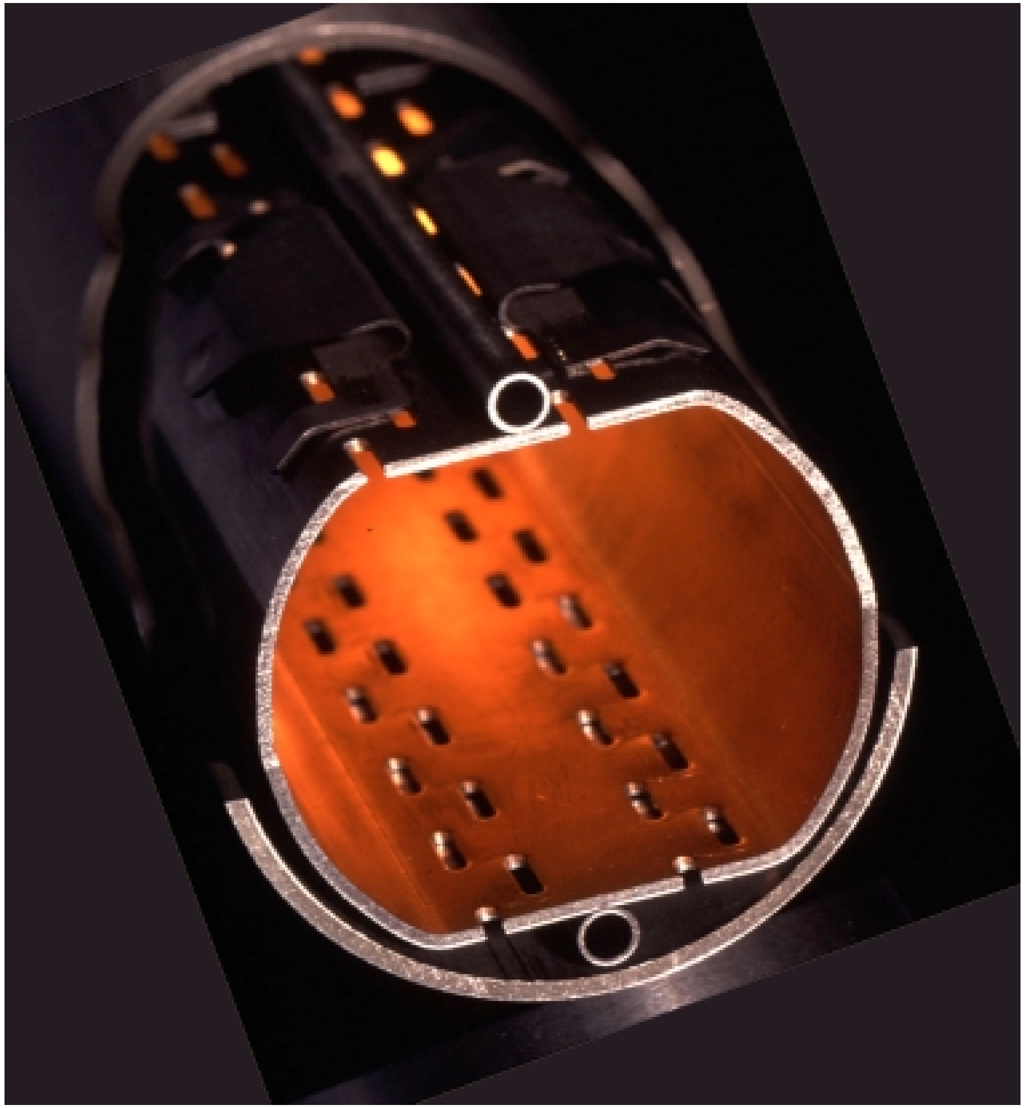
$$\Gamma(photons/s/m) = 7 \cdot 10^{19} \frac{E(TeV)\, I(A)}{\rho(m)}$$

Beam Induced Heat Loads (3)

Resistive Losses

$$P(W/m) \propto \rho_W I^2$$

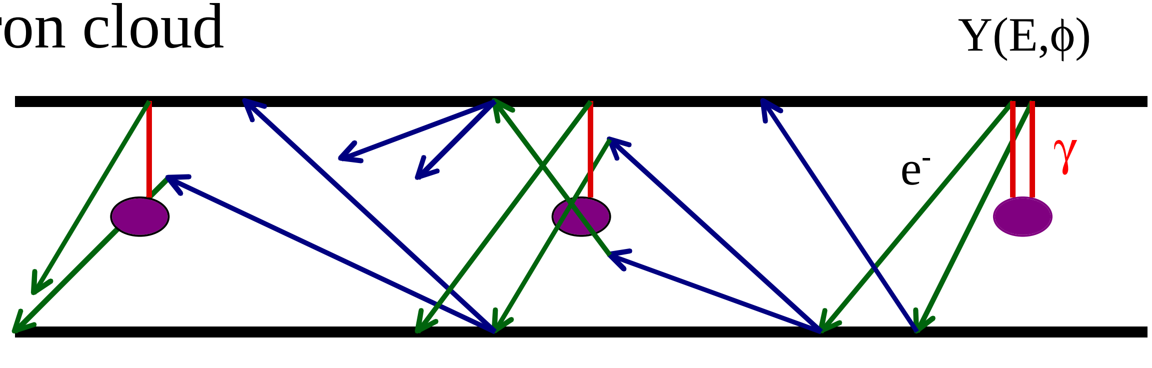
At cryogenic temperature a significant improvement of the resistivity of copper (LHC beam screen copper coating of 50 μm gives ~0.07W/m)
-> surface roughness of the coating can increase the effective resistivity.
Good electrical conductivity of the beam duct (beam screen) is essential.



LHC beam screen with cooling capillaries, copper coating and pumping slots

Beam Induced Heat Loads (4)

Photoelectrons and electron cloud



Key parameters :

Γ	Synchrotron radiation intensity
Y(E,ϕ)	photoelectric yield
δ(E,ϕ)	secondary electron yield, E_{max}, δ_{max}
R	Photon reflectivity of the walls (relevant in a magnetic field)
r_p	Beam pipe radius (shape)
N_p	Bunch intensity
L_{bb}	bunch spacing

External fields (magnetic, electric, space charge)

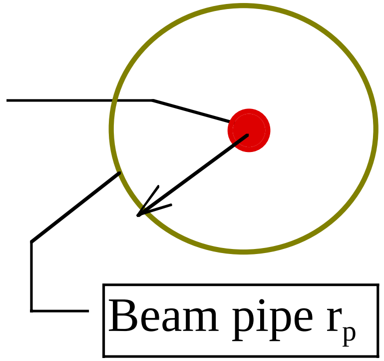
-> Dipole field confines the electron motion along the vertical direction

-> suppression of photoelectron production on the vertical walls

Electron Could Effect

Basic equations

$$E(r) = \frac{\lambda}{2\pi\varepsilon_o\, r} \qquad \text{with} \qquad \boxed{\lambda = \frac{e\, N_b}{c\, \tau}}$$



momentum transfer to an electron

$$\Delta p = e\, E\, \tau = \frac{e^2\, N_b}{2\pi\varepsilon_o\, c\, r}$$

Velocity gain during one bunch passage

$$\Delta v = \frac{\Delta p}{m} = \frac{e^2\, N_b}{2\pi\varepsilon_o\, m\, c\, r} = 2c\, r_e\, \frac{N_b}{r}$$

transit time condition $\frac{2r_p}{v} = t_{bb}$ or distance between bunches $L_{bb} = c\, t_{bb}$

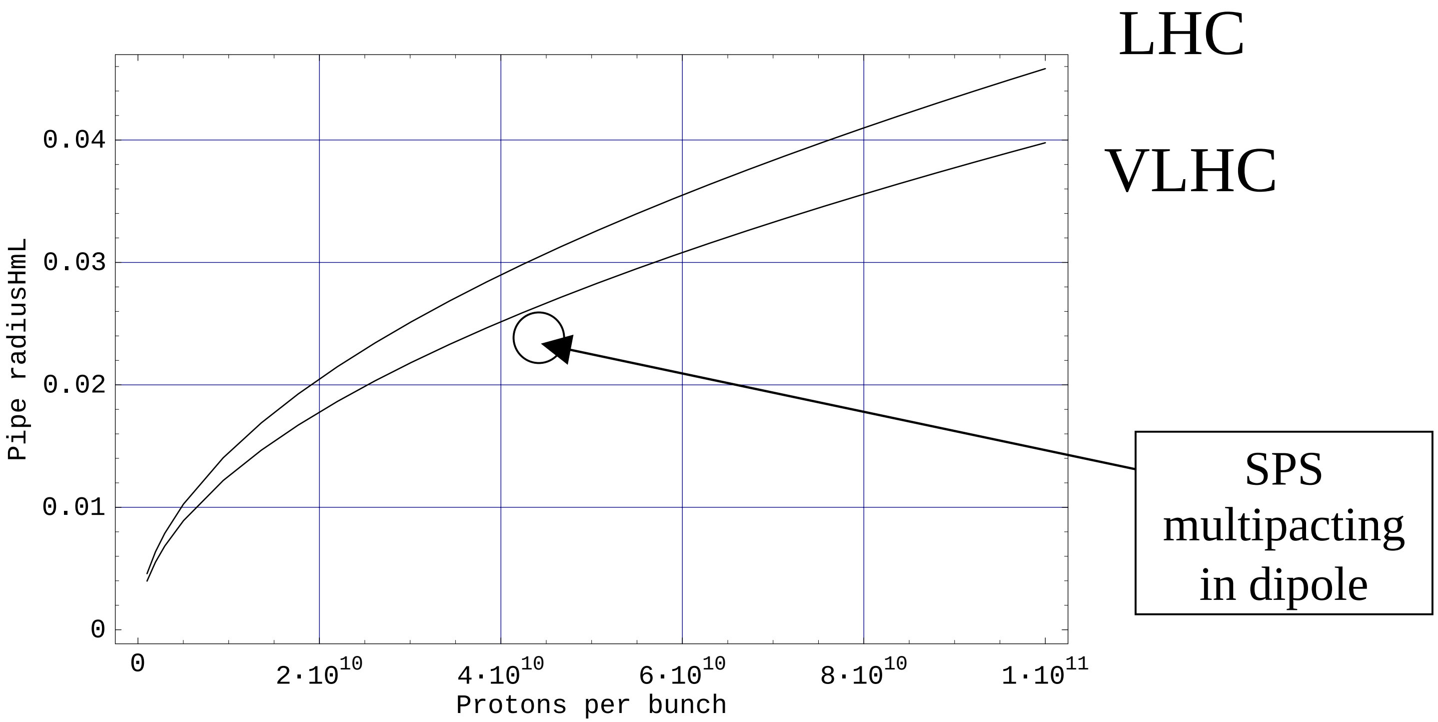
-> beam induced multipacting condition $N_b = \frac{{r_p}^2}{r_e\, L_{bb}}$

-> relates the beam pipe dimension to bunch parameters

Transit time condition for LHC and VLHC

LHC : L_{bb} = 7.5 m

VLHC : L_{bb} = 5.65 m



Energy Dissipation by the Electron Cloud (1)

Energy resulting from the kick of a bunch

$$\Delta W = \frac{\Delta p^2}{2m} \quad \text{thus} \quad \Delta W = 2\frac{mc^2}{e} r_e^2 \left(\frac{N_b}{r}\right)^2 \quad (eV)$$

With LHC parameters an electron at the wall receives an energy transfer of ~ 200 eV at each passage of a bunch, which is sufficient to generate a significant amount of secondary electrons -> multipactor.

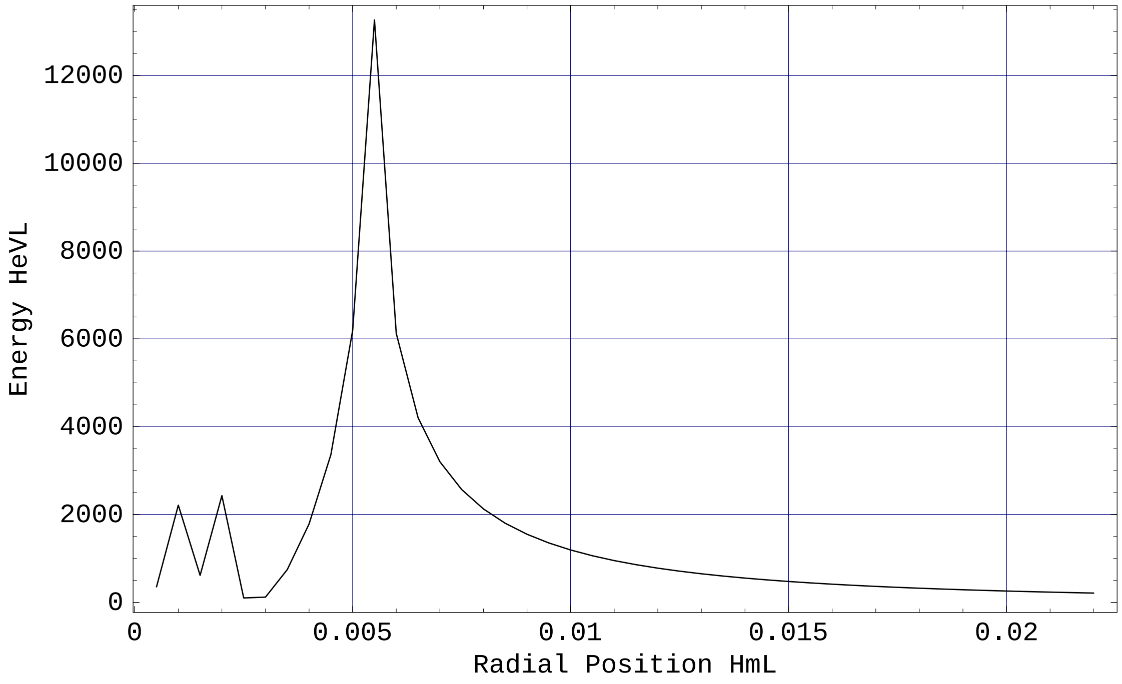
Scaling :

Production of photoelectrons proportional to the total photon flux N_b

Electron cloud induced power proportional to N_b^3

Energy gain of electrons as a function of the initial radial position
Nominal LHC conditions, vertical scale in eV

Electrons move duringr the passage of the bunch



Energy Dissipation by the Electron Cloud (2)

Approximate power scaling: $$P \propto R\, Y\, P_{ph} \frac{1}{1-\beta}$$

P_{ph} power due to the primary photoelectrons

β fraction of photoelectrons and secondary electrons which survive to the next bunch passage. (see compound interest rate)

If the secondary electron yield δ is sufficiently large β may become > 1 and the electron cloud could grow indefinitely.

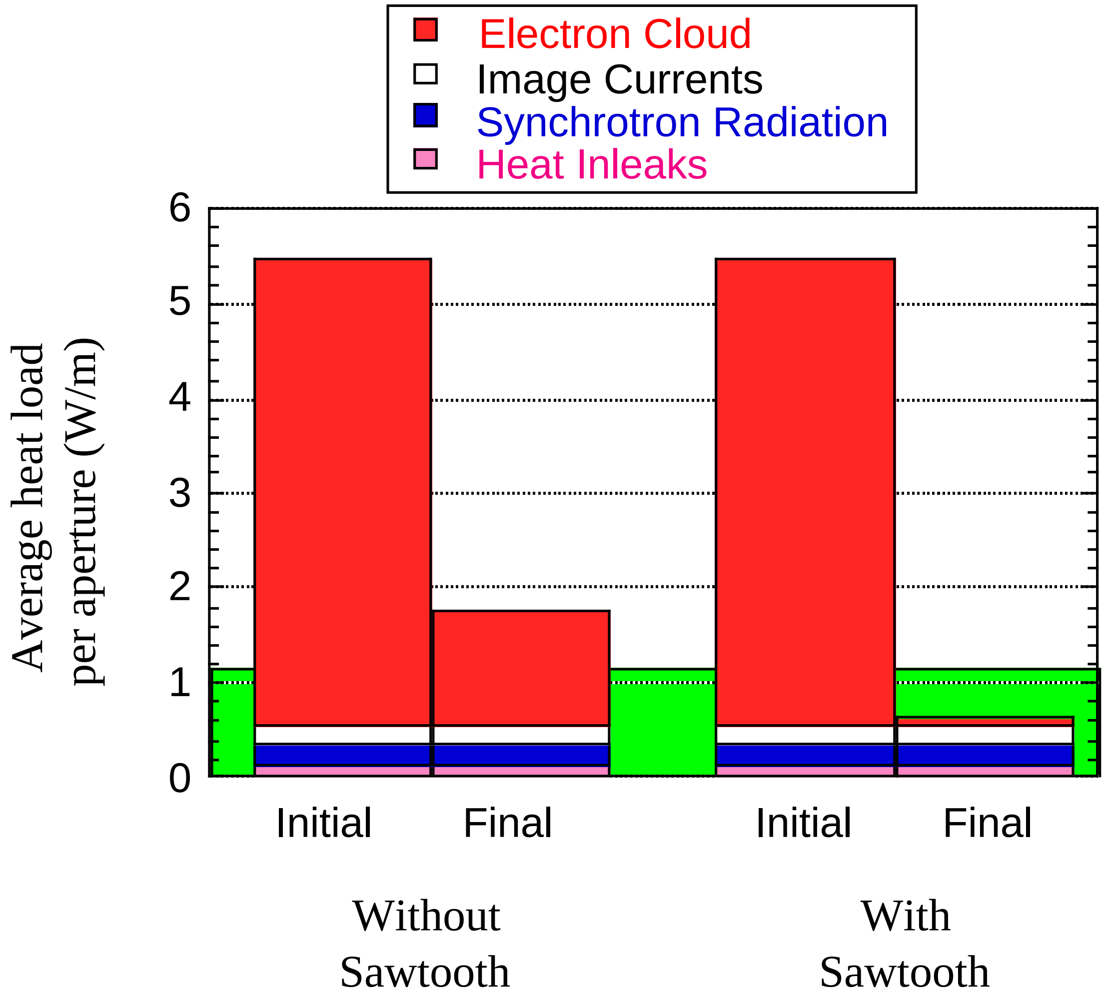
-> 'critical secondary electron yield' where the power becomes large.

LHC design :

Reduce R and Y by providing a 'saw-tooth' surface for the s.r. photons

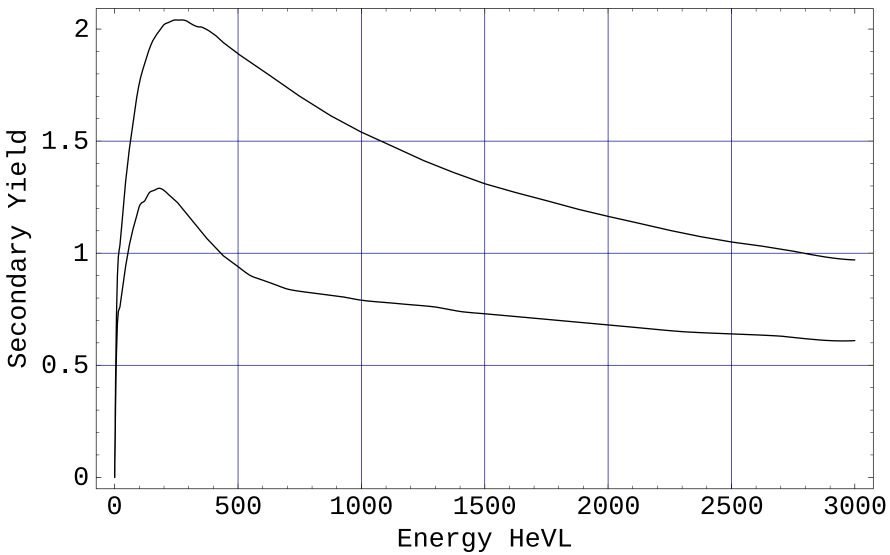
Reduce Y and δ by photon/photoelectron scrubbing (dose effect)

Effect of 'scrubbing' and of a 'saw-tooth' surface



Reduction of secondary electron yield

Secondary electron yield for Cu, initial and after exposure to a dose of 1.5 10^{22} photons/m synchrotron radiation at a critical energy of 194 eV



Maximum of the yield curve defines the values for E_{max} and δ_{max} which have been used for electron cloud simulations.

Estimated nominal heat loads due to electron cloud on a dipole beam screen. (Simulations by F. Zimmermann)

	Without Saw–tooth		With Saw-tooth	
Parameter	Initial	Final	Initial	Final
Reflectivity, R	1.0	1.0	0.1	0.1
Photoelectron yield, Y	0.2	0.1	0.05	0.025
Secondary electron yield maximum, δ_m	2.3	1.1	2.3	1.1
E_{max} (eV)	300	450	300	450
Nominal Heat load, P (W/m)	5.0	1.5	5.0	0.045

Pressure Increase due to Multipacting

Electron stimulated gas desorption has been observed in several machines : first in ISR in 1977 recently in KEK-B, PEP-2, SPS with LHC-type beams.

Gas load, Q_{cloud} is directly related to the power deposited by the electrons, $P_{lin,}$ to the molecular desorption yield, η_e and to the average energy of the electrons in the cloud, E_{cloud} .

$$Q_{cloud} = k \frac{\eta_e P_{lin}}{< E_{cloud} >}$$

The factor k relates molecular density to pressure units.

Summary

Beam screen : actively cooled to intercept heat load to the bore tube.

Cooling capacity : taking into account several beam related effects. Ideally, the bore tube dimensions should be chosen so as to avoid beam induced multipacting. Otherwise, a valid scenario for surface conditioning and scrubbing has to be implemented in the design.

Temperature of the beam screen should be adequate to provide low electric resistance.

Temperature should be adequate for cryo-pumping. (on outer surface of screen, which is not exposed to synchrotron radiation, electrons and residual gas ions)